

Prediction of Hydrodynamics for Unidirectional Flow

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LONG-TERM GOALS

Our long term goal is to develop an understanding of the relationship between channel geometry and three-dimensional flow features in rivers. One application of such an understanding would be the prediction of channel geometry given observations of flow velocities.

OBJECTIVES

1. Assess the applicability of the Regional Ocean Modeling System (ROMS) to riverine environments. For this purpose we will utilize the Flow and Sediment Transport Morphological Evolution of Channels (FaSTMECH) model developed by the USGS for 3D river flow problems and compare results to ROMS-predictions as well as observations.
2. Develop and test a parameter estimation routine in the ROMS modeling framework. Use this tool to determine channel topography given observations of flow velocities (either depth-averaged, or surface velocity observations) in the realistic setting of the Snohomish river, WA.

APPROACH

Many similarities exist between the riverine environment and the nearshore ocean environment. Both flow regimes are largely unidirectional (e.g. down-river flow or surf zone alongshore current), although local flow reversals and eddies can be present. Both environments contain mostly constant density fluid because mixing processes are pronounced. Both environments are also characterized by bottom sediments that respond (at times rapidly) to the overlying flow velocities, and rapid changes in bottom topography can occur and feed back to the flow velocities. Further, both systems have secondary depth-varying currents that may need to be accounted for (associated with bends in rivers and undertow currents in the nearshore). Finally, both systems are governed by the Navier-Stokes equations, although different simplifications and parameterizations have been developed by the separate communities.

These similarities suggest ocean models may be applicable to riverine environments. If successful, this would make it possible for one universal model to produce predictions in streams, rivers, estuaries, the nearshore ocean, shelf and open ocean. Hence, we are interested in answering the question:

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- Can an ocean circulation model produce acceptable flow predictions in a riverine setting?

We propose to utilize the Regional Ocean Modeling System (ROMS), which is a hydrostatic primitive equation model for a curvilinear boundary-following domain (Haidvogel *et al.*, 2008). It has been applied to ocean flow problems ranging from the dynamics of shelf currents (e.g. Peliz *et al.*, 2003; Capet *et al.*, 2008) to estuarine flows (e.g. MacCready and Geyer, 2001). A recent new version also includes forcing terms due to breaking surface gravity waves (although this routine is currently being updated) and introduces a variational data assimilation routine.

Similarities between the riverine and ocean environment also suggest that new techniques developed in the ocean circulation literature may be applicable in rivers. Examples of such techniques include data assimilation (DA) methods that have been applied to ocean and shelf circulation problems and are now being applied to surf zone problems. Such methods augment dynamical models with observations in order to correct for errors in initial or boundary conditions so that a more accurate representation of the flow field can be obtained. These methods have also recently been used to correct initial estimates of model parameters (e.g. Losa *et al.*, 2001; Kivman, 2003; Stammer, 2005). These parameter estimation methods can be extended to the prediction of channel depth, if the water depth is considered a model parameter. However, this treatment is somewhat more complicated (compared to estimating, say, frictional parameters) because the water depth is embedded in the governing equations as part of multiple terms in a highly nonlinear manner. We have recently applied a data assimilation methodology based on the Ensemble Kalman Filter (Evensen, 2006) to the estimation of nearshore bathymetry using discrete observations of mean longshore currents and have shown considerable skill (Wilson *et al.*, 2009).

Yet, it is known that the across-channel position of the maximum flow velocities contains information about the across-stream depth, especially when combined with information about the curvature of the river channel. Further, existing data suggests that surface velocities (that can more easily be observed synoptically using remote sensing observations) are a good proxy for the location of the depth-averaged maximum. Hence, there is reason to believe that depth-inversion methods using surface velocity observations have a good chance of success in this system. Hence, the questions to be addressed are:

- Can depth-averaged velocity observations be used to infer channel geometry in complex river channels that involve bars and pools as well as river bends?
- Can reasonable results be obtained using surface velocity observations?

WORK COMPLETED

We have prepared a publication that outlines the depth-inversion methods to be used herein applied to a case involving primarily surf zone longshore currents over a barred bathymetry. Further, we have carried out the required comparisons between ROMS and FaSTMECH and found that ROMs performed very well for a number of example test cases. Therefore, we moved on to simulations for real-life situations. Our first site involves the Snohomish river where observations are being collected as part of the ONR-funded COHSTREX MURI. Three-dimensional forward model runs for the river are currently being carried out and compared to the observed flows.

RESULTS

Several classic data sets can be used to assess model skill and advance DA methods. Examples include laboratory observations by Hooke (1975), field observations by Dietrich and Smith (1983) at Muddy Creek, Wyoming, or data from the Colorado River used by McDonald and Nelson (1997). Application of ROMS to the data set of Dietrich and Smith (1983) showed high skill. Because the situation at Muddy Creek is dominated by its strong curvature, depth inversion methods based on a simplified forward model proved successful.

In addition to these historical data sources, we are now involved in the Coherent Structures Experiment (COHSTREX) at the Snohomish river, WA. During the 2009 field experiment, the COHSTREX team gathered information about coherent structures as well as large scale flow at a number of sites along the Snohomish, including a gentle bend, a relatively straight section and a sharp bend (going north to south in Figure 1). The data collection included ADCP transects at several locations to assess the nature of the 3D velocity field as well as remote sensing observations of the surface signatures related to the large scale flow structures as well as smaller scale features such as “boils”. The Stanford modeling group that is involved in the COHSTREX study will be utilizing a non-hydrostatic model to analyze small scale boils that are likely associated with roughness featured at the bottom. Our role is to model the larger scale flow features for which hydrostatic modeling is appropriate. We envision the two modeling components to be linked and to be highly complimentary. The COHSTREX data will be used for both the validation work as well as tasks involving the depth inversion proposed herein. An important advantage to utilizing such a modern data set is the opportunity to be involved in the data collection process itself. Indeed, both PI and the graduate student on this project (Greg Wilson) have been actively involved in the gathering of the ADCP transect data. This has allowed us to have a strong intuitive sense of the physical setting and conditions during which the data was gathered.

Bathymetry observations of the Snohomish river (see Figure 1 right-most panel) indicate that bars and pools are present at each bend. This is an indication that the bends induce changes in the cross-channel distribution of the velocity as well as secondary circulation effects; therefore, much of the dynamics discussed above should be present here – including the considerations regarding the cross-stream position of the maximum velocity.

Results from a model simulation for the Snohomish River is shown in Figure , and a close-up of the area around the most severe bend is depicted in Figure 2. It is evident that the curvature effects associated with the bends introduce cross-channel variability in the surface elevation. Because river flows are driven by pressure gradients associated with the surface elevation, these cause along-channel and cross-channel velocities that are strongly affected by the presence of the bends. For example, the model predicts cross-channel velocities of up to 20 cm/s that only exist due to the effect of the bends. Accordingly, the along-channel flow no longer is strongest in the deepest part of the channel (as it would be if no channel curvature was present) but instead has a peak closer to the inner bank of the bend. These variations can be exploited for bathymetry estimation.

Preliminary comparisons of model results with data from the 2008 pilot experiment at the Snohomish river indicate high predictive skill. In addition, predictions are not sensitive to variations in the (global) friction or mixing coefficients, indicating robustness of the results. Our next step is to utilize our developed Ensemble Kalman Filter algorithm to this situation.

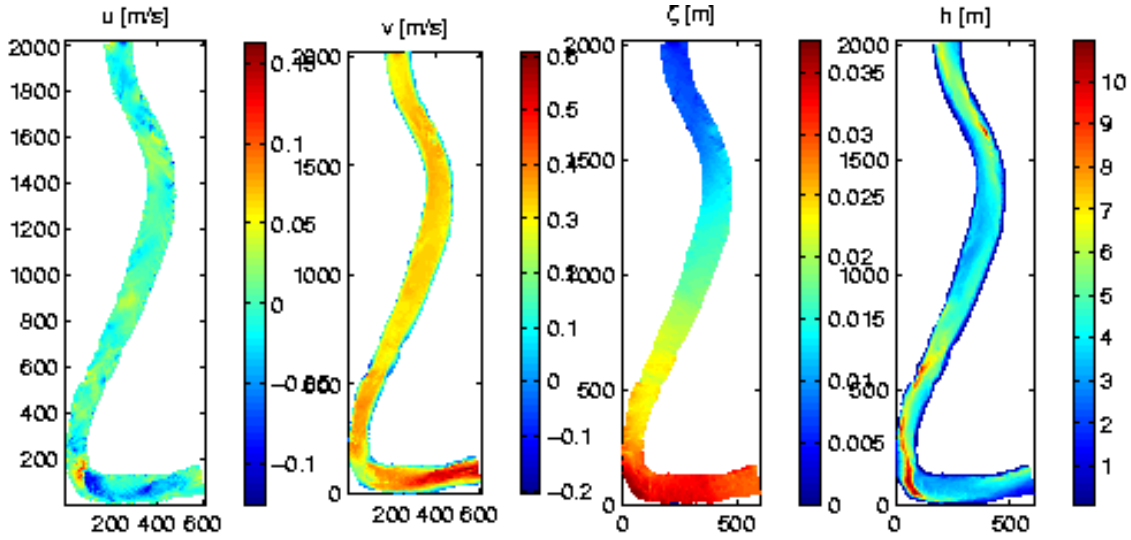


Figure 1: Panels from left to right are: depth-averaged cross-channel flow, depth-averaged along-channel flow, water surface elevation, and measured bathymetry. Cross-channel variations of the surface elevation at the bends cause modification in both velocity components.

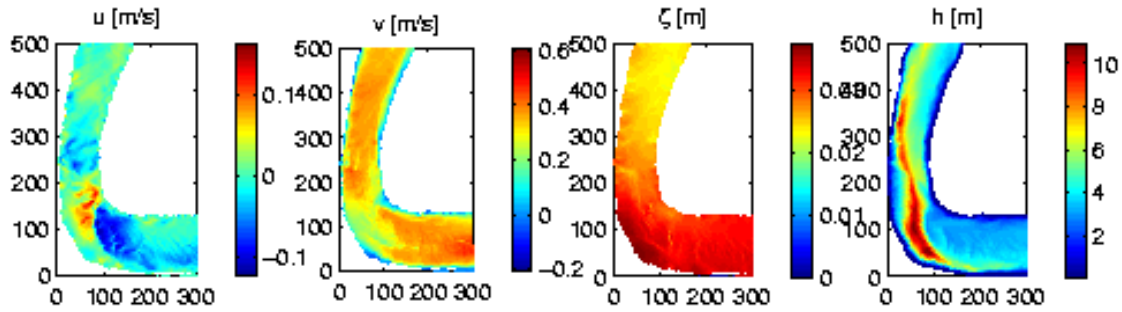


Figure 2: Close-up view of the flow features near the sharp bend. Panels are in the same order as shown in Figure 1.

IMPACT/APPLICATIONS

As part of this study we are developing methods to estimate the depth of river channels given information about the flow velocities in the river. The potential application of this work is primarily related to problems related to navigation up river channels.

RELATED PROJECTS

The Coherent Structures Experiment (COHSTEX) MURI lead by Andrew Jessup of U. of Washington is closely related to this work. The data that the COHSTEX group will obtain on the Snohomish river

over the next year will be utilized here to validate the numerical model and aid in the assessment of depth inversion techniques.

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PUBLICATIONS

- Wilson, G., H.T. Ozkan-Haller and R.A. Holman, Data assimilation and bathymetric inversion in 2DH surf zone model, to be submitted to *J. Geophysical Research*.